**METHOD FOR COOLING COILS AND SHIM IRON**

The present invention generally concerns the cooling of electrical coils. The present invention thereby in particular concerns a novel cooling method for better heat dissipation at gradient coils and shim systems of nuclear magnetic resonance tomography apparatuses.

Electrical coils generally possess a power or, respectively, stability limit that is defined by the limited dissipation of the ohmic loss heat. Such coils are used in magnetic resonance tomography (MRT), for example in the form of gradient coils and shim coils.

Gradient coils serve for the spatial coding inside an MRT apparatus in that a three-dimensional orthogonal gradient field is superimposed on the static homogeneous basic magnetic field in the x-direction, y-direction and z-direction. x-coil and y-coil are typically what are known as saddle coils that are rotated against one another by 90° with regard to the z-axis. The z-coil represents a Maxwell coil.

An exact image reconstruction in MRT is only possible when, during the measurement, the gradient coils exhibit a sufficient temporal magnetic field stability on the one hand and the static basic magnetic field is sufficiently homogeneous on the other hand.

Among other things, two techniques are known for homogenization of the basic field magnets:

1. A further orthogonal coil system with current flowing through it is located within the orthogonal gradient system, with which further orthogonal coil system it is possible to homogenize the basic field magnet. These additional correction coils (also called shim coils) serve to compensate field inhomogeneities of higher order

and are designed in a very complicated manner in that they are interwoven with the gradient coils.

2. For further homogenization of the basic magnetic field, a suitable arrangement of magnet bodies (shim irons) that are integrated into the gradient coil is calculated with the aid of a field calculation program. The curve of the magnetic field lines of the base field and of the gradient fields can be influenced via size and position of the shim irons. An advance measurement of the field distribution serves as a specification for the calculation. Another control measurement is conducted after the mounting. This process must be repeated multiple times before a satisfactory shim result is achieved. The shim irons are typically introduced into drawers axially in what are known as shim channels in the tube wall of the gradient system. In order to avoid or, respectively, to minimize eddy currents in the shim irons, the respective shim iron blocks (made up of playing card-sized shim plates) are stacked.

While the technique under point 1 represents an active shim, the technique under point 2 is designated as a passive technique. The combination of both techniques represents what is known as a shim system.

It is object of the gradient coil current supply and shim coil current supply to generate current pulses of precise amplitude and at precise times, corresponding to the measurement sequence used. The required currents are approximately 250 amperes, the current rise rate is in the range of 250 kA/s.

Under such conditions a great deal of heat arises in the gradient coils and in the shim coils due to electrical power loss on the order of approximately 20 kW, which heat must be actively dissipated in order to prevent that the electromagnetic behavior of the gradient and shim system (and therewith the imaging itself) is impaired.

A heating of the shim irons (on the one hand due to ohmic losses of eddy currents that cannot be avoided, on the other hand due to heat transfer of the gradient and shim coil heat via the sealing material) cannot be avoided and would significantly impair the shimming if the shim irons were not also cooled. However, the heating of the shim irons is smaller by orders of magnitude (approximately 5 W) than that of the gradient coils and shim coils, which is why an elaborate active cooling of the individual shim irons is not absolutely necessary.

According to the prior art, the cooling of convention electrical coils but also the cooling of gradient coils, shim coils and shim irons in nuclear magnetic resonance tomography ensues either via air surface cooling (air blown past) or via water cooling. The execution of an active water cooling has previously represented the most efficient cooling. However, the heat is hereby typically transferred from the conductors to be cooled into heat-dissipating flowing water via more or less poorly-conductive plastic layers. The heat resistance thereby caused limits the maximal capacity of the water cooling.

It is therefore the object of the present invention to achieve a cooling system with a much more efficient cooling capability in order to cool electrical coils and heat sources with low technical expenditure, in particular in magnetic resonance tomography.

This object according to the present invention is achieved via the features of the independent claims. The dependent claims thus develop the central ideas of the invention in a particularly advantageous manner.

According to the invention an electrical coil with cooling system is claimed, whereby the cooling system comprises a heat dissipation device with a fluid and a tempered reservoir of this fluid, and whereby the coil is coupled to the tempered reservoir by means of the fluid, and the reservoir is temperature-regulated such that

the temperature as well as the pressure of the fluid is kept in the immediate proximity of the critical point of the fluid.

In a first embodiment of the invention, the coupling ensues via a tube that conducts heat well, which tube contains the fluid and is situated in thermal contact with the coil conductor in that it passes through the electrical coil.

In a second embodiment of the invention, the coupling exists via the conductor of the electrical coil itself, in that this is fashioned tube-like and contains the fluid.

In a third embodiment, the coupling ensues via a heat-insulating tube inside which the coil conductor is coaxially directed and which simultaneously contains the fluid.

The critical temperature of the fluid advantageously corresponds to approximately room temperature.

According to the invention, carbon dioxide or $C_2F_6$ inasmuch offers itself [sic].

In order to generate an optimal cooling, temperature and pressure of the fluid in the reservoir are kept in immediate proximity of the critical point via a heat exchanger.

In a particular embodiment of the invention, the electrical coil represents a gradient coil for a nuclear magnetic resonance tomography apparatus with an electrical coil with cooling system according to any of the preceding claims [sic], whereby the gradient coil is a transversal gradient coil and/or an axial gradient coil.

In a further embodiment of the invention, the electrical coil represents a shim coil for a nuclear magnetic resonance tomography apparatus with an electrical coil and cooling system according to any of the preceding claims [sic].

According to the invention, a nuclear magnetic resonance tomography apparatus is also claimed with shim irons and cooling system, whereby the cooling system comprises a heat dissipation device with a fluid and a tempered reservoir of this fluid, and whereby the shim irons is [sic] coupled to the tempered reservoir by means of a fluid and the reservoir is temperature-regulated such that the temperature as well as the pressure of the fluid is kept in immediate proximity of the critical point of the fluid.

In an advantageous embodiment of the invention, the shim iron channels are thermally coupled to a tube system containing the fluid.

Here it is also advantageous when the critical temperature of the fluid approximately corresponds to room temperature.

It is inasmuch advantageous to use carbon dioxide or $C_2F_6$ as fluid.

According to the invention, the temperature and pressure of the fluid in the reservoir is [sic] kept in the immediate proximity of the critical point via a heat exchanger.

Further advantages, features and details of the present invention are now explained in detail using exemplary embodiments referencing the accompanying drawings.

Fig. 1 shows in perspective the gradient shim system of a MRT apparatus with a coupling of two shim channels to a fluid reservoir.

Fig. 2 shows a possible coupling of an electrical coil via the conductor itself.

Fig. 3 shows a possible coupling of an electrical coil via a coaxially-directed conductor in a fluid-filled insulator.

Fig. 4 shows a possible coupling of an electrical coil via fluid-filled thermal conductor that is in thermal contact with the electrical conductor of the coil at suitable points.

Fig. 5 shows the anomaly of the heat conductor coefficients of $CO_2$ in the proximity of the critical point.

As already shown above, electrical coils (such as, for example, sealed gradient coils or shim coils in MRT apparatuses) are presently air- or water-cooled, which leads to a distinct limitation of the heat dissipation capacity due to the poor heat conductivity of the sealing material. The present invention represents a significant improvement of such cooling systems. For heat transfer it is proposed to utilize the nearly unlimited large heat conductivity of fluids in the range of their critical point.

The anomaly of the heat conductivity coefficients $\lambda$ of fluids in the proximity of the critical point has been long known and is, for example, briefly described in the book "The properties of gases & liquids, Reid, Prausnitz, Poling, McGraw-Hill Book Company, 4th edition, ISBN 0-07-051799-1" on the pages 518 through 520.

The heat conductivity $\lambda$ of carbon dioxide ($CO_2$) is graphically represented in Fig. 5 dependent on the density at different temperatures (Fig. 5 was taken from the mentioned literature passage). Shown are four curves of $\lambda$ (measured in W/mK) in the range of the critical density ($\rho_c = 0.468$ g/cm$^3$) at temperatures of 75, 40, 34 and 32 °C, The graphic shows a distinct, significant rise of $\lambda$ in a relatively narrow range of the critical density ($\pm$ 0.1 g/cm$^3$) the more that the temperature approaches the critical temperature ($T_c$ = 31°C). The $\lambda$ of $CO_2$ at 32°C is thus already six times (0.3 W/mK) the value as at 75 °C (0.05 W/mK). Ultimately, at 31°C a nearly infinite value is theoretically expected (not shown in Fig. 5).

A clear explanation of this phenomenon is not provided. The conjecture is merely expressed that microscopic molecular phase or, respectively, order transitions

could be responsible or, respectively, microscopic flow effects due to molecular cluster movements.

A technical application of this effect was described for the first time in "German Jet Engine and Gas Turbine Development 1930-1945, Anthony L. Key, Airlife, England" on the pages 214/215. In the framework of examinations regarding cooling methods given gas turbine blades, Prof. Ernst Schmidt began in 1938 with studies of the heat conductivity of fluids in the range of the critical point. In order to demonstrate the theoretically infinite heat conductivity at the critical point, he filled a steel tube to one-third with liquid ammonia ($NH_3$). With practically all gases the density in the fluid state corresponds to approximately three times the density of the critical state. The cited ammonia filling to a third therewith also simultaneously leads to the critical pressure at the critical temperature. After a heating to 20°C, the tube possessed a heat conductivity like that of pure copper. After further temperature increase to the critical temperature ($T_c$ = 132°C) – it is reported – the heat conductivity of the tube now exceeded that of copper by 20 times.

For cooling of gas turbine blades, the described effect was translated to water, in that water vapor with critical temperature (374°C) was pushed through turbine blades at a critical pressure of 76 bar.

According to the present invention, the described effect should be utilized to keep electrical coils (as they are, for example, used in MRT apparatuses as gradient coils and shim coils) at operating temperature. According to the invention, for this the conductor piece to be cooled is thermally coupled to a fluid reservoir via a heat sink (for example a cooling tube). The fluid system is filled with a fluid at approximately critical temperature and critical pressure. This pressure and this temperature is [sic] maintained or, respectively, regulated via a heat exchanger or, respectively, a pressure regulator.

The segment to be cooled thus stands in direct contact with the fluid reservoir in this manner via extremely good heat conduction. The transport of a carrier medium for heat dissipation to the point to be cooled (as previously given active water cooling) is no longer necessary. For this reason no boundary layer effects (Prandtl boundary layer) that distinctly increase the heat transfer resistance exist in the inventive fluid system.

The viscosity of the fluid as a static medium is also extraneous in the inventive cooling system. The heat capacity of the fluid is only important insofar as it concerns the rapidity of the heat dissipation of the reservoir (and therewith the regulation inertia of the fluid system. In contrast to heat pipes, gravity (gravitation) has no influence; the heat conduction ensues similarly in the fluid in every spatial direction.

$C_2F_6$ lends itself as a filling gas for the operation at room temperature (approximately 293 K, 20°C), the critical pressure of which is a controllable 30 bar and whose critical temperature of 292 K (19°C) lies only a little below the operating temperature.

$CO_2$, with a critical pressure of 72 bar and a critical temperature of 301 K (minimally above the operating temperature), would also be possible. The latter has the advantage that a slight heating even further improves the already high thermal conductivity due to approach of the critical point and therewith stabilizes the temperature of the conductor.

According to the invention, various types of thermal coupling of the element (coil conductor or shim iron) to be cooled are possible.

In a first exemplary embodiment according to Fig. 2, the coil conductor is fashioned as a tube 1 in which the stated fluid 2 is located.

In a second exemplary embodiment according to Fig. 3, the conductor 3 is surrounded by a fluid-filled hollow tube 4 whose tube wall is electrically insulating and poorly thermally conductive, such that the heat is conducted along the tube inside 4; surrounding carrier structures are, however, not heated. The conductor 3 can be held (for example as in a coaxial cable) with support ribs 5 in the hollow tube 4.

In both exemplary embodiments the tube inside 2 is connected with the cooled fluid reservoir.

In a third inventive embodiment according to Fig. 4, the electrical coil 9 to be cooled is pervaded with a separate fluid-filled tube 7 which has thermal contact with the coil conductor 9 at a plurality of points 8 and is connected at least at one end with the cooled fluid reservoir 6.

As already mentioned in the specification preamble, it is normally also necessary to cool the shim irons 10 in order to ensure or, respectively, maintain the homogeneity of the basic magnetic field. Although the heating of the shim irons 10 is much lower than that of the gradient or shim coil conductor, a heat dissipation is necessary, whereby here the described effect can also be utilized according to the invention.

The shim irons are typically arranged in drawer-like insertions 11, whereby the number of the shim plates 12 in the different shim irons (also called shim stacks) can by all means be different. For example, Fig. 1 shows an insertion 11 with three shim irons (shim stacks) 10, whereby the front stack comprises five shim plates 12, the middle stack comprises three shim plates 12 and the rear stack comprises two shim plates 12. An insertion 11 with sixteen to eighteen shim iron stacks is normally respectively located in a shim channel 13, with sixteen shim channels in total that are radially, uniformly distributed in the gradient coil body 14 and run axially. The insertions 11 are axially inserted on the front side.

A cooling of the shim irons 10 using the effect described above ensues according to the invention via a coupling of all shim channels 13 (in which are respectively located the drawer-like insertions 11) to a tempered fluid reservoir 6. The coupling ensues via (thermo) hoses 15 that are flanged on the front side at the corresponding shim channels 13. Two such hoses 15 are shown in Fig. 1. Each shim channel 13 is filled with the fluid 2 which is tempered via the hoses in the reservoir 6 at critical temperature. The heat of the shim irons 10 is directly dissipated via the fluid reservoir 6 in this manner.

A less elaborate cooling of the shim irons 10 is to couple the hoses 15 with a passive heat sink, for example with an outer hull of the basic field magnet, and to forego a fluid reservoir 6 to be tempered. Such a design of the shim iron cooling is, however, only efficient when a certain heat capacity of the shim irons 10 is not exceeded.